# Technology Development Plan and Preliminary Results for a Low Temperature Hybrid Mars Ascent Vehicle Concept

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**A hybrid propulsion system is being considered for a potential Mars Ascent Vehicle (MAV) based on its low temperature capability, ability to restart and high performance. The hybrid's ability to survive in low and variable temperatures reduces power requirements and therefore system mass. Its ability to restart enables a Single Stage to Orbit (SSTO) design, minimizing system complexity. The hybrid's high-performance (~314 s Isp) leads to a low total Gross Lift Off Mass (GLOM). These advantages set the hybrid design above the alternatives in the system studies completed at JPL. However, this soultion has the lowest Technology Readiness Level (TRL) of the propulsion options. Therefore, a technology development effort has been undertaken to raise the TRL of the hybrid option and potentially enable its infusion into a future MAV or other in-space application. The culmination of this technology development is a flight demonstration, which is currently in the planning phases for launch in the early 2020's.**

## Nomenclature

| | | |
|---|---|---|
| *GLOM* | = | Gross Lift Off Mass |
| *ISP* | = | Specific Impulse |
| *MAV* | = | Mars Ascent Vehicle |
| *MAVRIC* | = | Mars Ascent Vehicle Research and Innovation Campaign |
| *MON* | = | Mixed Oxides of Nitrogen ($N_2O_4$ plus NO) |
| *PDR* | = | Preliminary Design Review |
| *PoDR* | = | Point of Departure Review |
| *RCS* | = | Reaction Control System |
| *SP7* | = | Wax-based Hybrid Fuel Developed for this Project |
| *SSTO* | = | Single Stage to Orbit |
| *TRL* | = | Technology Readiness Level |

## I. Introduction

HYBRID propulsion is being developed as a potential option for a future, robotic-scale Mars Ascent Vehicle (MAV). It was selected for development because of its promising low temperature storage and operation, flexibility to design changes and it was the lowest Gross Lift Off Mass (GLOM) option in the recent, JPL lead, systems study (Ref 1). To this end, a hybrid technology demonstrator, the Mars Ascent Vehicle Research and Innovation

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Campaign (MAVRIC), is being planned to reduce risk through progressive ground testing and suborbital launch in the early 2020's.

The Earth -based testing cannot match all Mars conditions. Therefore, the relevance of the MAVRIC to a potential MAV is discussed. First, a Mars conceptual design for a MAV is presented. Next, the current design for the proposed Earth-based technology demonstrator, MAVRIC, is outlined. Major differences between these two designs are presented. Finally, a technology development plan, including current highlights, is given to show the path towards a flight test. Several of the highlights of this plan, which have already been completed are presented as well.

## II. Point of Departure Review

A review was held in December 2016 to present a hybrid MAV design capable of meeting notional mission requirements as they were defined at the time. It should be noted that these requirements were more challenging than those used in the past (Ref. 1), including a more difficult target orbit (~479 km at 92.7 degrees, sun synchronous, Ref. 2) and an increased payload mass (18 kg plus 5 kg of margin). As in past studies, the MAV would be required to survive on the surface of Mars for a full Martian year and be host agnostic (compatible with a platform lander or rover, and solar or Radioisotope Thermoelectric Generator (RTG) powered). This potential MAV concept is the baseline to which the Earth-based technology demonstration program is being compared. The Single Stage to Orbit rocket conceptual design is capable of two ignitions (to reach altitude then insert into Mars orbit) and is fully guided using a Liquid Injection Thrust Vector Control (LITVC) system. The Helium tanks are stored around the hybrid motor and many of the propulsion components are assumed to be mounted directly on the motor case.

The most important propulsion parameters of the MAV conceptual design are all captured in Table 1. This design was presented in Ref. 3. The key and driving requirements on the propulsion system were the propellant combination, total impulse, propulsion dry mass and pressure losses across the system. A CAD image is presented in Figure 1, with relevant items called out. It can be seen that the GLOM has grown substantially since previous iterations. This is due to the more challenging requirements.

**Table 1: Point of Departure (Baseline) Potential MAV Design**

| PoDR Design | Units | Value |
|---|---|---|
| Payload mass (OS): | kg | 18 |
| Dry Mass Reserve | kg | 5 |
| GLOM | kg | 346 |
| Propulsion Dry Mass (includes RCS dry mass) | kg | 35.0 |
| Non-Propulsion Dry Mass | kg | 18.0 |
| Loaded Fuel Mass | kg | 48.4 |
| Loaded Oxidizer Mass (MON30, includes MON30 for LITVC) | kg | 219.6 |
| Pressurant and RCS propellant mass | kg | 1.82 |
| Thrust | N | 7120 |
| Specific Impulse (Isp) | s | 314 |
| O/F Ratio | - | 4.45 |
| Total ΔV | m/s | 4250 |
| Total Burn Time | s | 112 |
| Stack height | m | 2.85 |
| Hybrid Motor Outer Diameter | cm | 28.5 |

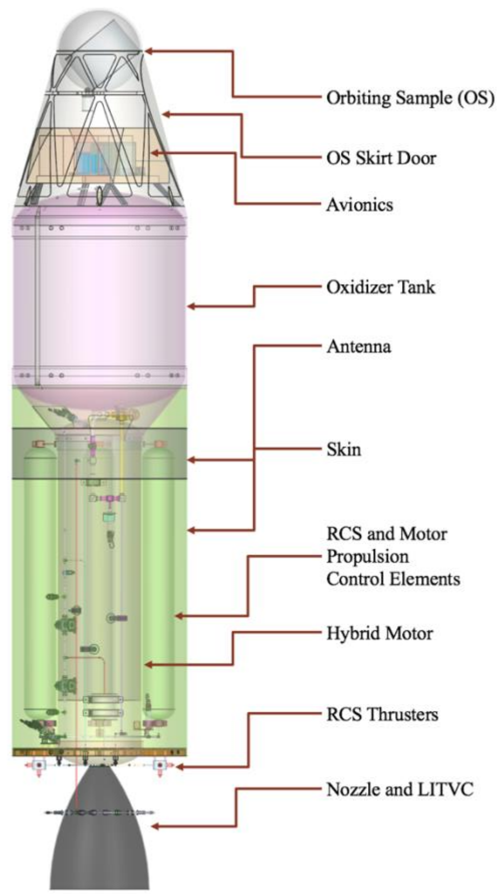



**Figure 1: Hybrid MAV Concept**

## III. MAVRIC

The culmination of the technology development would be an Earth-based demonstration of a rocket with similar capability to the MAV. This proposed activity is called the Mars Ascent Vehicle Research and Innovation Campaign or MAVRIC. The flight test has not yet been scheduled, but is anticipated to be in the early 2020's. The design of this system has not yet reached the Preliminary Design Review (PDR) level of maturity; however, the current iteration is presented in Table 2 and Figure 2 below. It is intended to be similar to the MAV concept presented above, but allow for flexibility to meet Earth-based challenges.

### A. Design

The design of the proposed terrestrial demonstrator, MAVRIC, varies from the PoDR MAV conceptual design and is presented below. The major desire of the propulsion team was to keep the motor the same size for the demonstrator as it would be for Mars. Therefore, other than slightly more conservative residuals, the propellant loading remains unchanged. An error in the original density estimate led to a change in the geometry of the fuel grain and therefore the thrust level to maintain a minimum oxidizer mass flux at the end of the burn. The type and configuration of the RCS system would also be the same for both the Mars and Earth-based designs. However, since the operating environment would be different, the MAVRIC design has a slightly higher thrust level. MAVRIC would also demonstrate two ignitions: the first enables it to reach altitude (after a coast) and the second would be a realistic demonstration of the LITVC system. The entire flight would be suborbital and after deploying the avionics for a separate parachute landing, the rocket would impact the ocean.

**Table 2: MAVRIC Design**

| MAVRIC Design | Units | Value |
|---|---|---|
| Payload mass (OS): | kg | 18 |
| GLOM | kg | 448 |
| Propulsion Dry Mass (includes RCS dry mass) | kg | 106 |
| Non-Propulsion Dry Mass | kg | 43.2 |
| Loaded Fuel Mass | kg | 51.0 |
| Loaded Oxidizer Mass (MON3, includes MON3 for LITVC) | kg | 228 |
| Pressurant and RCS propellant mass | kg | 1.92 |
| Thrust | N | 7120 |
| Specific Impulse (Isp) | s | 314 |
| O/F Ratio | - | 4.25 |
| Total ΔV | m/s | 2650 |
| Total Burn Time | s | 112 |
| Stack height | m | 3.4 |
| Hybrid Motor Outer Diameter | cm | 28.5 |

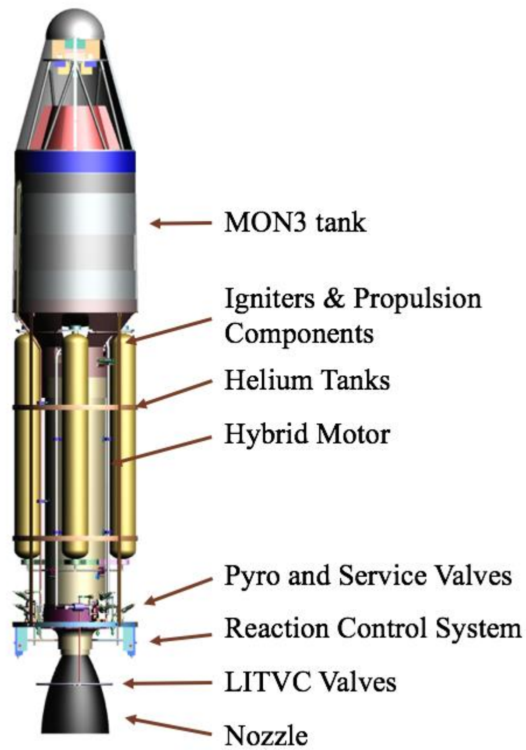



**Figure 2: Hybrid MAVRIC Concept**

### B. Major Differences from a MAV

A Mars Ascent Vehicle cannot be perfectly emulated through Earth-based testing; however, many aspects of the design are preserved and this effort would substantially reduce risk of the brand new propulsion system. There are several areas where departures from the Mars (PoDR) design are being allowed. As described previously, the PoDR MAV motor size is being preserved. However, MAVRIC's budget and schedule are driving the use of commercially available components. This leads to a substantial increase in the dry mass of the propulsion system and reduces the overall ΔV that the demo would provide.

Another major difference between the PoDR MAV and Earth based demo is the oxidizer. The low temperature capability of MON30 is highly desirable for Mars. However, the oxidizer would have to be kept cool for testing on Earth. If conditions were to be directly simulated, the oxidizer and feed system would need to be chilled to -20 C for all ground and flight testing. This is not particularly difficult; however, it has a considerable cost impact and could not be accommodated at this time. Performance with MON3 is expected to be similar, since MON30 just has more of the energetic additive: NO. A short discussion of the reasons for using MON3 instead of MON30 for the Earth-based demo is included in Ref 3.

### C. Possible Test Architecture

Though plans have not been finalized, the current test architecture calls for a balloon launch at Eglin Air Force Base, over the Gulf of Mexico. A direct ground launch, rocket boosted ground launch and balloon launch were all initially considered for the demonstrator. The direct ground launch required a substantial change in the motor design to get enough altitude to test the LITVC system, so was not selected. Both the boosted and balloon launch options enabled the use of a MAV-sized propulsion system and made it feasible to meet many more of the Guidance, Navigation and Control (GN&C) objectives. Using a first stage rocket to boost the demo to altitude imparted substantial loads on the test vehicle and cost more than the balloon launch, so it was also eliminated.

At this time, it is thought that the balloon carrying MAVRIC (the rocket inside a launch tube) could be launched from a barge off the Gulf coast of Florida. Within Eglin air space, the balloon would lift MAVRIC to about 30 km, where the conditions are representative of a Mars-like surface atmosphere. The rocket would ignite, exit the launch tube, coast to altitude, complete a LITVC test, and then descend into the ocean. The avionics would be separated and recovered if possible to access higher-rate data than what can be transmitted during the test itself.

### D. Challenges

Several challenges characteristic of a technology development program have arisen as the proposed design for MAVRIC matures. Slosh in the oxidizer tank during launch has been determined to require mitigation. The rapid timeline for this project had originally lead to the desire to use a bare tank without any baffles. However, it will not be possible for this case, as the slosh modes could cause the rocket to fail. As will be described later in the paper, fuel grain production ended up being much more difficult than anticipated, and full scale grains are currently being made up of small segments instead of a monolithic fuel grain. Additionally, it appears that there is some residual stress in fuel grains manufactured to date. Methods for relaxing the grain stresses are current being evaluated. Finally, several technical decisions have to be made to meet program budget and schedule, including using heavier tanks and different propulsion components.

## IV. Technology Development Plan

Technology development is ongoing through this program and a plan has been formulated to move this novel propellant combination from conception (in 2015) to TRL 6 through a flight test (in ~2020). Leading up to the flight, a substantial amount of chemical, material and hotfire testing needs to be completed. Additionally, testing of solid additives which are hypergolic with MON is being carried out to simplify the multiple ignition requirement.

### A. Propellant Combination and Characterization

The first step in the technology demonstration plan is to characterize the propellant combination. Much of this work will be done through hotfire testing (described in the next subsection). However, it is also important to have the relevant mechanical and chemical parameters to accurately design the motor. A selection of these results is presented in Section V. The initial motor design was completed assuming SP7 was very similar to paraffin wax; while this is not a bad assumption, current testing has shown enough difference to warrant an update.

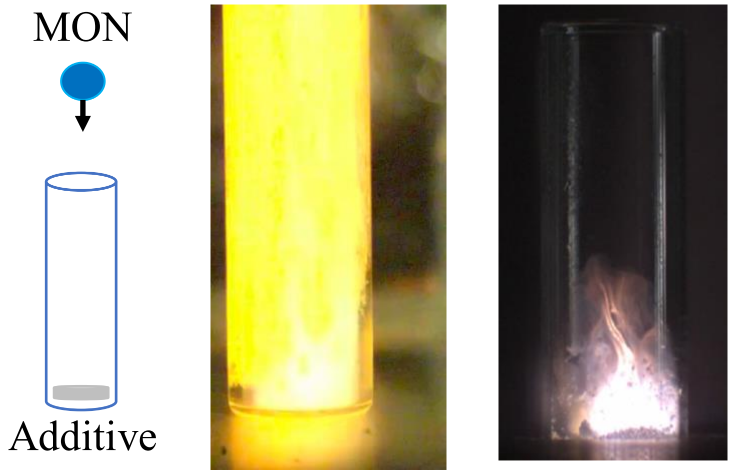
The oxidizer design leverages data on MON from the bipropellant world. Most parameters are available in the Air Force Handbook (Ref. 4) and all MON for testing is ordered to MIL-PRF-26539. Therefore, no oxidizer testing is necessary at this time.

### B. Hotfire testing (SPG, Whittinghill)

Hotfire test data of this novel propellant combination is crucial for this project. Preliminary, small scale (three-inch motor) tests of SP7 with the nontoxic oxidizer $N_2O$ were used to inform the initial design. The motor was then adapted and testing was completed with MON3 and SP7 at SPG (see Figure 3). The $N_2O$ was found to be a good analog for the MON in terms of the regression rate dependence on oxidizer mass flux, which is a crucial design parameter. Testing of a 10-inch motor was planned at another subcontractor in 2016 as well, but sustained combustion was not achieved in the short period allotted for the tests.

**Figure 3: Three-inch motor testing at SPG in 2016.**

Preparations for full scale (~11 inch) testing are currently underway at two subcontractors: Space Propulsion Group and Whittinghill Aerospace. Both vendors plan to hold test readiness reviews in June. Testing would begin immediately after and carry on through the summer. The primary (ambitious) goals of this short test program are to reach stable combustion (chamber pressure oscillations of +/- 5%), high performance (efficiencies of 95%), and to complete a full duration burn and a restart.



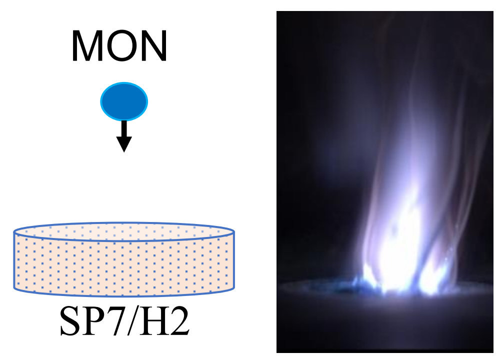

a) b) c)

**Figure 4: Hypergolic ignition testing a) descriptive cartoon, b) Additive H1 tested at Penn State and c) Additive H2 tested at Purdue.**

### C. Hypergolic Ignition Testing

A solid hypergolic additive to the fuel grain is highly desired to simplify the multiple ignitions in the hybrid design. Hypergolic ignition is currently being held as the ignition mechanism for the second burn on the PoDR MAV. Research in this area has been completed by Penn State (Ref. 5) and Purdue (Ref 6). Small scale drop testing has already been completed for tens of candidates at both universities. A cartoon of the process is shown in Figure 3a. Penn State tested with MON3 and Purdue tested with NTO (no added NO) and MON25. They each operated independently and the best candidate hypergolic from each university, referred to as Hypergol 1 (H1) and Hypergol 2 (H2), are shown in Figures 4b and 4c. The best candidates were selected based on their ignition delays, which were determined from high speed video. However, many alternatives were also discovered and the system design may lead to an alternative being selected in the future.

The next step of testing was to mix the hypergolic additive into some SP7 wax and determine if the hypergolic ignition is still possible. Wax is very good at protecting the additive, however, both Penn State and Purdue discovered hypergolic options. A cartoon depicting Purdue's set up for this test (Fig 5a) and a successful test are shown in (Fig. 5b).




a) b)

**Figure 5: Hypergolic ignition testing a) descriptive cartoon and b) test of H2 mixed in SP7 wax pellet at Purdue.**

MAVRIC is assumed to use more conventional ignition methods due to the short timeline of the project. Therefore, this research is only feeding into a potential Mars case at this time. Future work includes hotfire testing in a two-inch motor (at Purdue) with both MON3 and MON25 to confirm the hypergolic ignition, capability for restarts and changes in fuel regression rate or specific impulse of the motor. Reactivity with changing concentrations of NO is of special interest to understand the difference of testing with MON3 (the terrestrial demo case) and MON30 (Mars case).

If the two-inch motor testing with MON3 is completed early enough to allow full scale testing within the current demo timeline, it may be possible to adopt hypergolic ignition for MAVRIC. However, there is no plan to do so at this time due to the number of other ongoing technology developments.

### D. Future work and Flight Demonstration

The culmination of this technology development program would be a flight test of a similar system. The propulsion system would be brought to TRL 6 by conducting a flight in a relevant environment (at altitude). This test would demonstrate the hybrid motor performance, multiple burn capability and a long burn time, Liquid Injection Thrust Vector Control (LITVC) and RCS control, as well as a number of other objectives. The details of this test are still being finalized; however, an overview of the notional program has been given in the previous section.

A competition will be held to design a motor for MAVRIC after the hotfire tests have been completed and it is expected that a single subcontractor will be selected. The subcontractor will ground test their design next year and deliver a motor(s) for the balloon flight. The performance of the system will be confirmed through these tests and the LITVC performance must be quantified at this time as well. While not currently in the plan, if additional funding were to become available, it is desired to complete full scale testing with MON25.

## V. Propellant Combination

One of the major drivers of the hybrid propulsion system is the new propellant combination. The propellant combination is currently at TRL 3, but is being matured. A new wax-based fuel, called SP7, was developed specifically for this application to survive temperatures as high as 50C and as low as about -100C. Space Propulsion Group completed the fuel development under contract to JPL in 2015. The oxidizer is Mixed Oxides of Nitrogen, MON30 which is 70% $N_2O_4$ with 30% NO. MON30 has been selected over MON3 for the MAV concept because to its lower storage temperature encompasses the expected Mars environment without freezing.

The current Earth-based testing is using MON3, which has 97% $N_2O_4$ and 3% NO instead of the low temperature option. It is expected that MON3 will be representative of MON30 and is much easier to handle in Earth ambient conditions. MON3 is also commercially available and less expensive that MON30, which would have to be specially mixed for this testing. Hotfire testing of SP7/MON3 was completed in FY2016 and is ongoing at larger scales in FY2017 as described in the previous section.

In addition to hotfire testing, a campaign to characterize the propellants has been undertaken to raise the TRL of the propellant combination. Since SP7 is a newly developed fuel, no past testing could be leveraged. Several chemical and mechanical tests were carried out on the fuel this year including the density, heat of combustion, modulus, and ultimate strength, all of which will be required for the final design. Results from several of the chemical analyses and mechanical pull tests of SP7 is presented in the following sections. Thermal data, such as the coefficient of thermal expansion, and preliminary thermal cycling results have been presented in Ref. 7. The thermal cycling was completed without issues.

Mixed Oxides of Nitrogen (MON) has been selected as the oxidizer. Outside this development program, it has only been used in one other hybrid development: Sandpiper testing in the late 1960's and early 1970's (Ref 8). MON is being used because of its storability and theoretically high performance. A decent amount of data exists for MON from bipropellant literature (Refs. 4, 9, 10, 11) and was leveraged throughout the design process. Development testing of MMH/MON3 and MMH/MON25 injectors could also be leveraged to understand the effort required to move to the higher NO concentration in the hybrid system. A comparison of the differences between the MON30 and MON3 oxidizer for the PoDR MAV are given in Ref. 3.

### A. Fuel Chemical and Mechanical Analysis

Material properties are necessary to design and test with the new fuel. Some of the most critical chemical and mechanical parameters were evaluated this year. These include density, heat of combustion, modulus and ultimate strength, among others.

1. Density

The density of the SP7 was measured through standard hydrostatic weighing (buoyancy). An average density of 0.9590 g/cm$^3$ was determined from five samples. The samples were machined in house at JPL and were all about 0.9 cm long by 0.7 cm in diameter and had the same mass to four significant figures. The measured density is slightly higher than that published for paraffin, but lower than our initial estimates. Therefore, there is a difference in the motor geometry from the PoDR design to the MAVRIC design to account for this difference.

2. Heat of Combustion

An average heat of combustion was measured using bomb calorimetry. The results of four samples were averaged to 11.01 kcal/g (46.10 kJ/g).

3. Mechanical Properties

A desire to determine the modulus and ultimate stress lead to pull testing at JPL. Dog bones were made to the following specification: ASTM D638 – Type I (Ref. 12). Two types of dog bone samples were made to determine if there is any non-homogeneity in fuel grains when they are cast. Axial samples were cut along the length of the fuel grain, in the same direction as the central port. Radial samples were made from an individually cast section, to simulate the radial direction or direction orthogonal to the axial samples. They could not be cut directly from the same grain due to a lack of material. It would be desirable to have both materials come from the same sample in the future. Note that samples R005 and A001 were determined to have defects and were not used. The sample size for this testing was very small (four samples tested at room temperature and two at low temperature). ASTM-D638 requires a minimum of five samples. Therefore, additional tests are recommended for statistical significance.

**Table 3: Mechanical Pull Test Results for SP7 fuel**

| | Sample | Modulus (x $10^6$ MPa) | Average Modulus (x $10^6$ MPa) | Std. Dev. (x $10^6$ MPa) | Cov (%) | Ultimate Stress (MPa) | Average Ultimate (MPa) | Std. Dev. (MPa) | Cov (%) |
|---|---|---|---|---|---|---|---|---|---|
| Radial / 22 C | R001 | 1.798 | 1.739 | 0.101 | 5.787 | 4.332 | 4.15 | 0.258 | 6.218 |
| | R002 | 1.850 | | | | 3.998 | | | |
| | R003 | 1.658 | | | | 4.413 | | | |
| | R004 | 1.649 | | | | 3.876 | | | |
| Axial / 22 C | A002 | 1.504 | 1.597 | 0.0875 | 5.479 | 4.807 | 4.65 | 1.316 | 28.277 |
| | A003 | 1.603 | | | | 4.551 | | | |
| | A004 | 1.659 | | | | 4.884 | | | |
| | A005 | 1.516 | | | | 4.373 | | | |
| Radial /-20 C | R006 | 3.106 | 3.083 | 0.0325 | 1.055 | 3.586 | 3.19 | 0.566 | 17.774 |
| | R007 | 3.060 | | | | 2.785 | | | |
| Axial /-20 C | A006 | 3.672 | 3.786 | 0.162 | 4.268 | 2.305 | 2.65 | 0.488 | 18.426 |
| | A007 | 3.901 | | | | 2.996 | | | |

### B. Fuel grain manufacture

The SP7 fuel grain manufacturing process was originally developed by Space Propulsion Group. Their casting process was based on technology developed for SP1, a paraffin-based wax fuel. The technique needed to be applicable to neat SP7 fuel and SP7 with aluminum additives, as both options were initially considered before the selection of neat SP7. The original casting process worked well; however, it was never advanced to the full length at the 11-inch scale.

Due to the upcoming down select in hybrid rocket concepts, Marshall Space Flight Center (MSFC) was asked to even the playing field between the subcontractors and provide fuel grains to both. Therefore, MSFC developed a process to manufacture fuel grains that would be independent of the subcontractors. The grains provided by MSFC are to be used in the tests of record for both subcontracts.

Thus far, the fuel grain casting process has been limited by the size of the melting pot available and the length of time it takes for the SP7 ingredients to liquefy. SP7 becomes fully molten at ~110 C (~230 F) and must be kept below the point where it starts decompose: about 120 C (245 F).

Multiple configurations were tried with a mandrel for the center port. Solid metal mandrel sections lead to cracking as the SP7 transitioned from liquid to solid sections (SP7 shrinks by ~20% volume during the phase change). If the outside edges cooled/solidified before the core, cracks and voids would form as the center shrinks and solidifies. Various materials were used to wrap the mandrel to allow shrinkage (oil absorbent pads, quilting batting, foam, etc.). It was also difficult to find a material to seal the mandrel (oven bags were eventually used with the most success). However, if the molten SP7 got past the mandrel barrier, the mandrel could not be removed without damaging the grain. Eventually it was decided that a mandrel was not required, since even if a center port was successfully cast, it would have to be machined to the right dimensions to meet tolerances.

Commercially available cake pans were selected to build up a fuel grain in wafer-like segments. The first cake pans were about two inches tall by nine inches in diameter and produced crack free grains when allowed to cool normally. It was observed that some grain segments cracked when allowed to cool under ambient conditions as the pans were scaled up to support the full scale test grain diameter (about four inches tall by 12 inch diameter). The short length over diameter configuration appears to enable one dimensional cooling, while the increased thickness promotes cracking during cooldown. Even if the grains did not crack in ambient cooldown conditions, some would still crack in post processing or shipping. This indicates that residual stresses exist in the grains and need to be considered.

Several options for casting crack free grains were investigated. However, the immediate need for test grains forced the process down selection to the wafer grain concept. Multiple grains would be made in cake pans, the top and bottom would be milled flat, then the inner diameter (ID) and outer diameter (OD) would be cut to size using a water jet. After further process development, it was determined that there was not sufficient material remaining on the OD

for the waterjet stream to maintain tolerance, so it was finished on a lathe instead. These machined wafers were then stacked to the right length to make the grain. (See two completed grains, one without insulation and another with insulation in Figure 6.) After the first set of wafers was completed, the surface finish was improved by machining them on the lathe instead of mill. So far, two grains have been produced for testing each of the subcontractors using
the wafer fuel grain production process. A larger, ~115 kg (250 lbm) wax melter has been purchased and is being used to speed the casting process.

The potential effect of using grain wafers as opposed to a monolithic grain on regression rate of is being studied. The concern is that the flow could be tripped at the wafer interfaces due to small between the wafers or a difference in the regression rate of an adhesive used to bond them. The solid fuel torch is a testbed for various nozzle and insulation materials for the Space Shuttle and Space Launch System boosters (Ref. 13). It will be used in this case to test the regression rate at the wafer interfaces. A series of three tests will be completed. The tests will have identical grain dimensions, but the first uses stacked wafers, the second stacked wafers bonded together and the third a monolithic fuel grain. The same oxidizer flow rate and burn time will be measured and the regression rates will be compared. Inspection of the chamber pressure, grain weights and uniformity as well as the hardware will reveal if there are any differences caused by the three grain configurations.

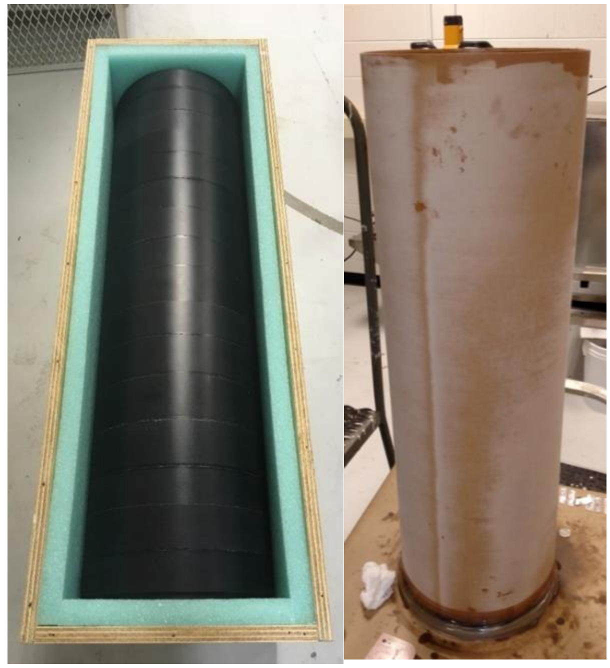


**Figure 6: Completed fuel grains at MSFC for testing at Space Propulsion Group and Whittinghill Aerospace**

The grain wafers also could affect the stress in the grain during vibration loading and thermal cycling. A preliminary review of vibration loading has indicated that the wafer configuration could help minimize vibration induced stresses as long as they are in good contact. Unbonded grain wafers could also show benefits in thermal cycling over temperature ranges experienced on Mars and would directly replicate the testing done in Ref. 7. The coefficient of thermal expansion of potential case materials and the SP7 vary by an order of magnitude. The Space Launch Systems solid rocket boosters have similar L/D solid propellant cast segments which have stress relief flaps to keep the thermal cycles from putting excessive stress on the solid grains at a temperature range much lower than the MAV configuration. It is possible that a similar mechanism may need to be employed here. This thermal loading scenario is being studied at in a more detailed structural analysis currently.

Additional improvements in the grain processing are still being researched. Oven cooling over the span of about eight days has produced crack-free grains up to about 16 inches tall and 12 inches in diameter. Dissection of a few grains have not revealed any interior voids or cracks. There are some differences in surface finish from the casting process; however, these would be machined off in post-processing. So far, 16 inches has been the height limit of the pans, but a new 50-inch pan is ready for casting. If that development is unsuccessful, active cooling or heating may be required to produce a full-length grain.

## VI. Conclusion

Potential hybrid propulsion designs for a Mars-based MAV and a proposed Earth-based technology demonstrator, MAVRIC, were presented. A technology development program was outlined for a hybrid propulsion system as it applies to a potential MAV. Major strides in the development were highlighted, including hotfire test results and hypergolic ignition testing. The path towards a flight test is discussed, including the current architecture being envisioned. Selected results from chemical analyses on the SP7 fuel are presented, as are the results of mechanical pull tests on SP7 dog bones. These results are intended to enable systems studies with the new fuel. Finally, a discussion of the fuel grain casting process is included.

## Acknowledgments

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